Additive Manufacturing for Aerospace

Schiller, G.J.
United Launch Alliance
9501 East Panorama Circle
Centennial, CO 80112
303-269-5331
Gregory.J.Schiller@ulalaunch.com

Additive Manufacturing aka 3D printing opens up a whole new era for digital design and manufacturing. No longer is the aerospace engineering designer constrained by the ability to manufacture a component. The new philosophy is "if you can design it, we can produce it". Yet there is a laundry list of caveats with the current state of the technology especially as it applies to aerospace applications and in particular, launch vehicles. Use of polymer based materials has caught hold in production tooling, yet use of polymers and metals for actual flight applications faces challenges until the technology catches up with the specific needs of the Aerospace industry. Launch vehicle applications may prove to be the bounding arena for aerospace applications. Consider the need for perfection in quality, temperature extremes from cryogenic commodities to rocket engine exhaust, shock and vibration conditions, and the grand size. However, given the variety of exquisite designs and low volume, aerospace applications are well suited for Additive Manufacturing. The challenges of today are already being solved and incorporated into the technology of tomorrow. It is simply a matter of time before AM finds not only a foot hold in aerospace but becomes the manufacturing tool of choice.

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1. INTRODUCTION

Additive Manufacturing is capturing the imagination of young and old alike. Look at any school in the U.S. and one has a good chance of finding a 3D printer accessible to the student body. Kids are asking parents for 3D printers for their birthdays instead of video games. This last comment may be a bit speculative yet the hype surrounding the boundless capabilities of 3D printers is reaching all genres. Social media as portrayed by Wikipedia describes AM as the following:

> *"3D printing or additive manufacturing (AM) refers to any of the various processes for printing a three-dimensional object. Primarily additive processes are used, in which successive layers of material are laid down under computer control"*

Subtractive methods such as machining a finished product out of a block of metal is now considered "old school". Under older manufacturing technologies, the designer used a term called "design for manufacturing" which was essentially a constraint against design options since more intricate designs were extremely costly to produce. AM changes that paradigm. Referring again to that new age source of all knowledge, Wikipedia, which describes a disruptive technology as:

> *"A disruptive innovation is an innovation that helps create a new market and value network, and eventually disrupts an existing market and value network (over a few years or decades), displacing an earlier technology"*

One can certainly apply this label to AM. 3D printing opens up a new age of design opportunities unconstrained by old school manufacturing methods. Innovators are using it to redesign existing applications. New unique applications are being brought to the market in a variety of industries. The aerospace industry is perfectly suited to the opportunities enabled by AM, yet may prove to be a bounding area given the extreme environments. There are still a large list of caveats and challenges to the idea "if you can design, AM can produce it". But these challenges are being overcome. This paper explores the utilities of AM for aerospace applications, while highlighting many of challenges and trends still on the horizon.

2. AEROSPACE DESIGN OPPORTUNITIES

Most aerospace applications are match fit to AM capabilities. This is especially true on the space side of the aerospace arena. Launch vehicles and satellites are not high rate products. Airplanes are more so. But it can be a business challenge to ask a technology company to design a highly complex product and then tell them you need two a year for the next five years. AM provides capabilities to produce singular units of production at relatively low cost

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that completely changes the business case assessment (described later in this paper).

Aerospace products are uniquely complex. Many parts must satisfy extreme requirements which many times lead to complex geometries and structures. Complexity creates challenges for existing manufacturing technologies. As complexity increases, traditional manufacturing costs skyrocket. Complex parts require multitudes of individual parts that must be fastened together with nuts, bolts, welds or brazes. Each of these connections reduces the reliability of the component which leads to increased inspection requirements. It should be no surprise why aerospace components cost as much as they do. However, this is where AM can shine with the ability to produce complex parts with the same agility as simple parts. Aerospace developers are now free to design to exquisite levels of complexity without driving manufacturing cost exponential. By reducing part count and connection points, reliability can be improved. At the same time, the exquisite complexity can also increase functionality. The AM component can be tailored very specifically to the need. This is exactly the value that GE Aviation saw in their design of a fuel nozzle for their latest jet engine design seen in Figure 1. Using AM capabilities, GE designed the fuel nozzle for the highest level of efficiency while minimizing weight. The resulting increase in functionality and reduction in weight cut fuel consumption and thus reduces long term cost [1]. Reliability and durability is driven up as they were able to consolidate what was 20 parts to one [2].

Figure 1: GE Jet Engine Fuel Nozzle

Another giant in the aerospace industry, Lockheed Martin has a grand vision of innovation using advanced manufacturing techniques including the application of AM. This contributes heavily to their innovation construct referred to as their Digital Tapestry [3]. The example shown in Figure 2 illustrates how AM can transform a relatively simple connecting bracket into a more complex component at a tenth of the weight. This much lighter weight bracket still meets all of the requirements imposed. A complex design like this would be exceeding costly to produce via traditional methods. Now the component is less costly due, in part, to the reduction of material being used to print the part referred to as the buy-to-fly ratio.

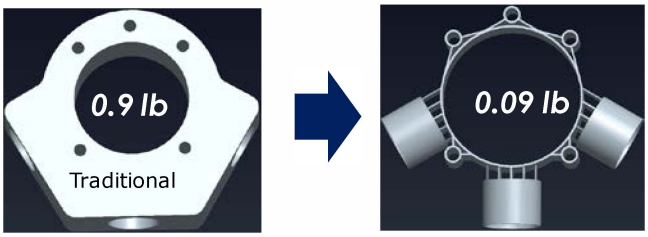

Figure 2: Spacecraft Bracket

The software technology used to support the designs of these exquisite parts is referred to as Topology Optimization. For structural optimization, these tools take an initial draft design and start eliminating material in areas not necessary to support structural requirements. The resulting design can look quite strange often mimicking biological forms and is certainly challenging to produce from traditional manufacturing [4]. Even though AM techniques can support these types of designs, the engineer may back off from what the tool is saying is the most optimal design to one that satisfies other optimization objectives. Additionally, AM can produce related optimization of interior structures such as lattices and trusses that provide structural stability but at much reduced weight [4].

Materials availability has come a long way in the last decade. Thermoplastic materials have the most pedigree behind them and have found opportunities in current aerospace applications. Additionally, there are opportunities for thermoplastic materials to replace metals in less demanding situations and thus should not be overlooked for design options. Plastics are being used in many non structural applications such as environmental control system ducts, protective covers, cockpit parts, and others [4]. Military jets like the F-18 and F-35 host or will host many 3D printed parts [4]. More will be said later in this paper about plastic utilities for tooling.

For metals, the list of more common aerospace focus alloys includes high grade Stainless Steel; Nickel-based super alloys like Inconel 625 and 718; Titanium and Titanium alloys; and to a lesser degree Cobalt Chrome alloys [4]. There has been plenty of research conducted on Inconel 625 with 718 not far behind. Given its lighter weight, strength and ductility characteristics, Titanium alloy is a heavy area of research. The higher relative cost of Titanium drives a desire to use an additive approach vice a subtractive one given the high buy-to-fly ratios possible.

3. AEROSPACE APPLICATIONS

Aerospace applications may prove to be the most stressing application of AM technologies. To be even more specific, launch vehicles and satellites face temperature extremes from liquid cryogens to rocket engine combustion and exhaust. Likewise, launch vehicles are exposed to high structural, vibration, and acoustic loads. High pressures and speeds exist in combustion chamber, turbo pump assemblies and jet turbines [4]. While some of these affects are more

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short lived, aircraft applications must consider longer term aging and fatigue issues. Aircraft manufacturers also must consider repair and rework more so that space oriented applications. These requirements drive the need for more capable alloy materials that can accommodate a wide range of concurrent requirements. Material characteristics are also driven by the need for consistency and quality.

Most of the more costly aerospace applications, again the example being launch vehicles, are very large. Consider a launch vehicle's height of 200 ft composed of fuel tanks that are as big as a semi tractor trailer. Aircraft are not far off this same size scale. Even the subsystems such as propulsion, electrical and mechanical that service the operating portions of aerospace applications tend to be large.

Even with many of these hard-driving requirements, there are a whole host of opportunities that fall within the current and very near term capabilities of 3D printing. One of the best examples of extreme temperature applications is the work being accomplished at NASA Marshall on a liquid engine propulsion injector plate. The injector is composed of a 3D printed aerospace grade alloy that can accommodate these extreme conditions [4]. The design is highly intricate with many challenging aspects from surface finish to materials composition. The photos in figure 3 shows this injector plate and the component being test fired as part of a system test [5].

Figure 3: Injector Plate & Test Fire

Fuel flow characteristics are critical to performance of components such as this. 3D printers enable unique interior flow configurations that would be almost impossible for normal manufacturing techniques. The liquid Oxygen Flange shown in Figure 4 is used on the upper stage of United Launch Alliance Launch Vehicles. The photo on the left is the original part and the one on the right is 3D printed. One can see there are differences between the two. On the left, the interior "vanes" are brazed into position. On the right, they are simply printed as part of the 3D build process. When qualified for flight, this part would operate exactly the same as the original. However, very little else was done to modify the design of this part to fully take advantage of 3D printing. If the design team steps back to investigate the needed flow requirements, a new design may result in a more elegant configuration with improved performance.

Figure 4: Liquid Oxygen Flange

United Launch Alliance is also baselining several thermoplastic components to fly on future missions. Illustrated in figure 5 is an example Environmental Control System (ECS) duct that will flow conditioned air on sensitive equipment during launch. This item is printed on a Stratasys Fortus 900 out of a material called Ultem 9085. Ultem 9085 is a favorable material due to its high performance for strength, durability and resistance to heat and chemicals [6]. There are numerous ducts of this nature with multiple configurations. Current ducts are composed primarily of multiple fiberglass pieces with metal attach fittings. 3D printing enables multiple parts to be incorporated into singular components. This reduces the overall part count significantly. 3D printing also eliminates any mandrels or layup tooling and the cost associated. Other components like protective covers are being investigated as well. Many of these components are exposed to severe aeroheating environments as they are configured on the exterior of the Launch Vehicle. Although plastic, the material characteristics of Ultem are considered flight worthy even in the face of high heat. Yet more analysis is necessary. Insulation may be necessary but the goal is to fly this material in a self insulating configuration.

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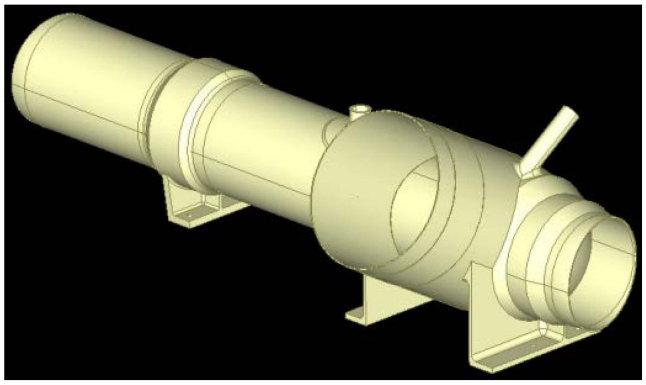

Figure 5: Environmental Control System Ducts

As mentioned previously, 3D printed plastic tools are finding a solid foothold in the aerospace industry. If aerospace companies are only looking at flight applications, they are missing a significant opportunity for cost savings in their tooling departments. This is the "low hanging fruit" of the 3D printing arena. Many of the same advantages are exemplified in tooling applications such as faster turn time to manufacture the tool and dramatically lower cost. This is especially true where a metal tool is replaced by a plastic one. Plastic tools are lighter and more ergonomic which is even more important in a production labor environment. If a metal tool is heavy enough to require two technicians to properly handle, a plastic tool may only require one tech which reduces half the labor. Plastic materials also limit potential damage to flight hardware as a result of their use. Scratches and dings from metal tool contact could be catastrophic to Launch Vehicle performance in a worse-case scenario. At a minimum, they will cause non-conformances and rework thus driving additional cost. Unlike flight components, tooling does not require qualification and certification. Verifying the tool is functional for the prescribed use is still necessary but the level of testing and analysis is not as stringent as for a flight component certification.

Similar to flight component concerns to be discussed later, tooling is subject to disadvantages using AM. Understandably, plastic tools are not as robust as metal in the longer term as wear and tear take their toll. For example, drill templates require inserted metal bushings which can cause heating in the surrounding plastic material and become loose. Mitigation techniques for this are possible, yet often the most expeditious and cheapest route is simply to print another tool. Post processing to effect a tight tolerance on metal parts (and sometimes plastic) is often necessary. Overall tolerances on plastic parts can also be a challenge, but with more experience this too can be mitigated in the design phase. The ability to print and test inexpensively enables the opportunity for executing some level of trial and error corrections without the financial impact. Even one-time-use only tools can be considered. This is especially true in molds.

Example of a drill template is shown in figure 6. This shows a combination of metal and plastic. The metal was accomplished through traditional machining. But the plastic portion greatly simplified the construction and operation of this tool reducing tool creation time by 80%. Shown in Figure 7 is a fit check tool. This tool is highlighted since it actually broke during operation. There is a crack visible along the facing edge. But, the problem was identified, the tool was redesigned and reprinted within days and put back into operation. The next tool highlighted in Figure 8 is the fitting alignment tool used on the aft end of United Launch Alliance's Centaur upper stage. This tool was previously metal and thus very heavy and difficult to handle. This tool weighing only 25 lbs can be handled by one person vice two. Using plastic, the cost was less than a tenth of the original estimate using other methods. Concerns over tolerances are still being investigated, yet they are anticipated to be solved. Lastly, the tool illustrated in Figure 9 is another drill jig that is snapped onto the component and only fits one way. This tool resulted in 70% labor savings.

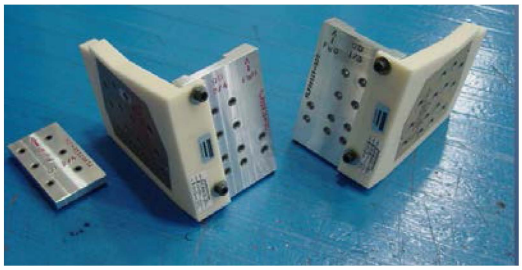

Figure 6: Drill Fixture

Figure 7: Directional Fit Check Tool

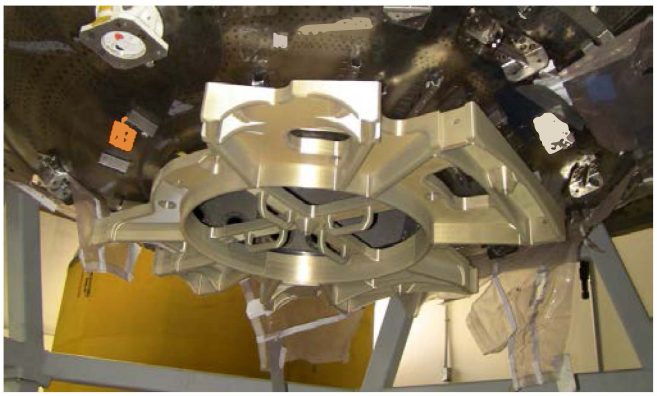

Figure 8: Strut Locating Tool

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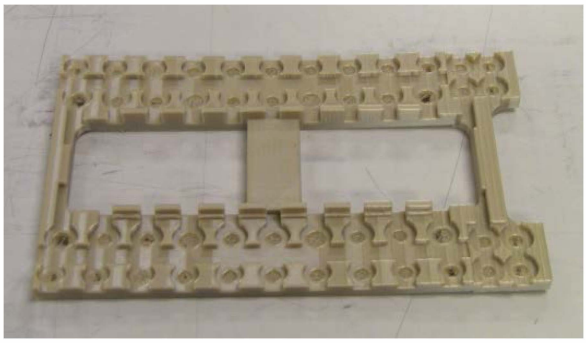

Figure 9: Snap on Drill Jig

4. COST ASSESSMENT

Like in many industries adopting AM, utilizing AM disrupts the traditional supply chain equation. In general, the aerospace industry is more horizontal than vertical. Companies tend to utilize their respective supply chains for the variety of unique components necessary for an aerospace product such as launch vehicles and spacecraft. The supply chain maintains a bulk of the expertise in the many areas. However, utilizing AM enables the opportunity to bring manufacturing back in-house to the prime company, thus increasing the level of vertical structure inherent. As a result, the cost and schedule for procurement of components is effectively eliminated. This is true for most any make/buy decision, but AM is unique in that the make part of the equation is different than the buy part which is assumed to utilize a traditional approach. Of course, as the supply chain begins to adopt AM into their respective manufacturing repertoire, the decision process begins to compare apples to apples again. Whether in-house or procured through an AM supply chain, the ability to produce a part in a shorter timeframe supports and expands the traditional philosophy of the Just-In-Time operations that reduces the carrying cost of inventory. Many believe that AM can reduce leads times around 80% [1].

AM also disrupts the economies of scale and scope equation. From a scope standpoint, it is difficult to find another manufacturing tool capable of producing an infinite number of components from a single machine [7]. Similarly, AM machines can swap from one component to another with a software input model and does not require any extensive tooling changes [7]. Now a milling machine could be characterized in the same manner but is still limited in the area of complexity whereas an AM machine is not. Looking at the scale aspect, an AM machine cost could reach a breakeven point of even just one unit [7]. With current costs of metal AM machines, that component would need to be exceeding complex and expensive but yet the point is still valid. Small numbers of complex components can make a business case for the investment. Cost of 3D printers (especially metals) and raw materials is still relatively high and constrains entry into the market, but the trends will continue to bring costs down as competition and magnitude of demand heats up.

Cost may not be the absolute driver in all aerospace applications. For airplanes, the cost and return on investment is slightly different. Higher non-recurring cost may be acceptable if performance saves money in the longer term. For an aircraft in service for 30 years, fuel savings is a driving factor. Even in expendable launch vehicles, weight and performance may trump higher non-recurring cost. Lesser weight implies higher performance-to-orbit payload capacity. Many customers including the Department of Defense value performance.

Cost modeling for AM applications is also an immature science. AM applications are slowly being introduced into production and integrated into the value stream. Thus example data is limited. Traditional cost models can be adapted but yet the true life cycle value modeling will take time to validate. Still leaders at Airbus advertise they see small components saving 60-70% on production parts [8]. Other estimates capturing longer term fuel savings are enabled by the projected 10-30% weight savings using AM [4].

5. CHALLENGES

Much of the previous content paints a fairly rosy picture of AM in aerospace applications. There is a fair amount of hype surrounding the technology. Not all hype is reality… yet. But the technology is still fairly immature in the aerospace industry. Industry standards are lacking. There is no Mil Handbook XYZ governing the standards necessary for implementation of AM. Factors of safety for design are determined on a case-by-case basis. Methods for test and inspection are being researched with no prevailing methods rising above the rest. CT scan may be the only method that can look into the microstructure to determine porosity and cavities within the build. Ultrasonic inspection works in limited applications. Non-recurring component qualification methods are conducted utilizing standard methodologies without investigating whether other methods are possibly more conducive to AM technology. Acceptance tests for finished components are typically treated as worse case situations given the current uncertainties of material quality and consistency.

Not every material used in the aerospace industry is reaching maturity. Most notable in this category is aluminum. Some work has been accomplished on lesser grades of aluminum, yet little has been done for higher grades more common in aerospace. Copper is less prevalent but has similar maturity issues. One possible positive aspect of materials science is that AM may enable additional alloys not previously available due to the nature of some machines with the ability to mix a variety of metal powders during the build process [4].

Printer capabilities are continuing to expand, yet limitations exist. From a build size metric, many machines measure build size in inches. Much of the analysis work accomplished to date has been done by companies investigating components much smaller than a cubic foot in volume. Not every component is highly suited to AM

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technology. Print orientation and design of build support structure is more art than science right now. Similarly, different 3D printing techniques have different pros and cons associated with component design and print orientation. Much research is being conducted on materials consistency and quality yet much is left to be learned. In most applications, the post build product must be heat treated in a variety of fashions to achieve desired materials quality. Similarly most machines produce a product with a very rough surface finish unsuitable for a final component. Thus post build machining or other surface finishing techniques are necessary. Machining is still a necessity for any surface requirements for mating to another component requiring a very tight tolerance.

Most current machines are essentially "open loop". If there is any fault detection, the machine typically just shuts the print job down and pauses for human evaluation. Many without any fault detection continue to print and the print job can become unrecognizable. Research is being accomplished to accomplish in-situ process monitoring. For metal machines this involves sensor monitoring of the melt pool. Different sensor techniques are being investigated from simple temperature, to infra-red to high speed visual or combination of all three [4]. The resulting data is also challenging to evaluate for meaningful information. The raw data amount is staggering [9]. Consider monitoring a build with thousands of layers of melt pool data, then compiling the data into a build assessment in real time in a feedback loop to control the printer. Even reviewing this type of information after the print job is daunting. Better tools are required to make this effective and they must be incorporated into the machine by the manufacturers.

Knowledge capital of the design engineers and operators is limited to those directly engaged in AM pursuits. University based courses, programs and research activities are growing rapidly. Yet those already in industry are typically learning through their own research or in collaboration with others. Much, if not all, knowledge and intellectual property is being held close to the vest for these companies with substantial investment. They are protecting the fruits of their investment. This constrains growth of knowledge of many of the basic facets of AM including basic material characteristics.

In a similar light, design and analysis tools associated with AM are lacking basic capability and integration into existing tools. The concept of seamless progression from inception to final product is not quite a reality yet. Several design packages exist for design optimization many in the non-commercial sense contained within university research activities. But none have truly risen above the rest.

For aerospace applications, development timelines can be very long, occasionally longer than a decade. It is often hard to interject rapid moving technology into a lengthy development timeline. The common theme is that technology is outdated before the product is fielded.

6. TECHNOLOGY TRENDS

Each of the various AM techniques have their own strengths and weaknesses. A greater synopsis of the many subtleties can be found in the reference material. In this analysis, only the higher order trends are addressed as they pertain to aerospace interests notably size and finished material composition. In this respect, three major simplifying characterizations are highlighted. In "bed" systems, material more typically in powder or liquid form resides in a bed of raw material. Examples of this nature include direct metal laser sintering and selective laser sintering. In "fed" systems, the material is fed into the system via different methods including powder spray, filament, or filament tape. Examples of these techniques include Laser-Engineering Net Shape (LENS^{TM}) offered by Optomec Co, Direct manufacturing offered by Sciaky, Inc, and Fused Deposition Modeling offered by Stratasys, Inc. Hybrid systems may combine either of the two bed or fed systems' approach with a milling machine capability. An example of a fed Hybrid is offered by DMG MORI.

Metal bed systems and research is more prevalent in current aerospace applications. This is useful for relatively small applications. Size has been increased, yet at a certain point, size becomes a challenge with the current bed methodologies. To make a large object, the bed of material must be exceedingly large as well. This becomes unwieldy and costly. Consider a large bed where the risk of contaminating hundreds of thousands of dollars of powder material in one event will become a costly mistake. Weight and safety is another issue. Fed systems have their own limitations yet are more likely to enable larger sized components. In some applications, the only limitation is dependent on the size of the enclosed, pristine environmental enclosure one is willing to construct. Extrusion techniques in thermoplastics are making sizes as large as a car [10]. Both of these techniques as standalone methods do not provide a truly finished product in most cases. Post processing techniques must be applied to achieve desired results either by heat treatment or milling.

Hybrid techniques seek to resolve the challenge of providing a fully finished product as a function of the single machine. Whether bed or fed, hybrid machines incorporate milling and sometime heat treatment into the build process. Fundamentally, the process is composed of printing layers of material and then milling those layers. The process is repeated until the finished product is done. By heat treating the metal after printing, other challenges in materials properties can be overcome as well. The finished product is truly finished with surface effects that meet requirements and tolerances to the same level achieved by tight tolerance milling machines today. Also, by utilizing milling as part of the build process, hard to reach interior surfaces can have the same finished surface quality necessary in many aerospace applications. Ultimately, a fed hybrid system may be able to achieve both size and finish requirements of the future demand by the aerospace industry. Due to the

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newness on the market of Hybrid techniques, more work is necessary to determine their full potential.

Figure 10 provides a much simplified and notional view of this assessment. Bed systems may be considered more capable simply because more applications are currently using this technique. Fed systems have greater capacity for size. Hybrid systems bridge between the two but much more is yet to be learned.

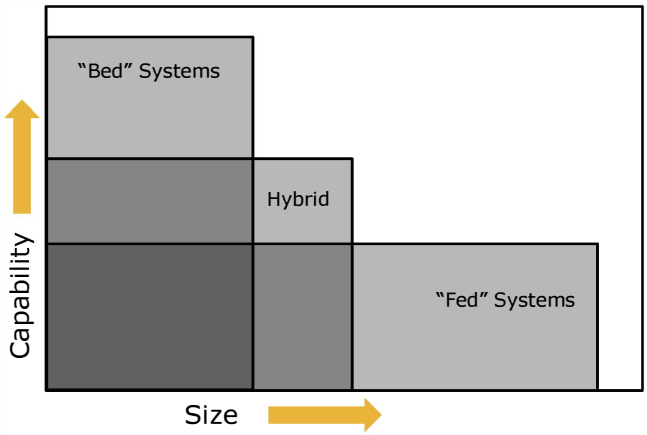

Figure 10: Technology Trend Chart

7. WAY AHEAD

Aerospace companies are investing heavily in AM applications most notably General Electric. Many see the utility now and potential for growth in the future. However, commercial entities are also holding their investment Intellectual Property close to maintain their competitive edge in this area. Other organizations, university and national consortiums, are working (and funding) collaborative development activities to advance the state of the art. This activity aids sharing of data and developing much needed industry standards. However to speed the pace, more of this is needed especially to support the smaller companies without the magnitude of resources such as GE. Academia is also paying strong attention. There are a few relative giants heading up research activities like Pennsylvania State University, University of Texas El Paso, and University of Louisville. They are teaming with industry for research applications and techniques of interest to those commercial entities. They are also supplying industry ready innovators in the various facet of AM. Similarly, OEM's providing commercial 3D printing machines are listening and reacting to the needs of their customers especially aerospace. Many are also teaming to determine improvements in their machines for build process monitoring and analysis techniques. They are also looking to increase build size, capability, and speed. The way ahead is progressing quickly, yet an even faster pace is possible with increases in collaborative efforts to address the challenges.

8. SUMMARY

Aerospace is one area among many that is well-suited for adoption of Additive Manufacturing as part of the enterprise value stream. Lower cost and increased functionality is possible in this low rate, high complexity arena. Many AM techniques and materials have already found current production ready applications despite many of the extreme environments inherent in this industry. Tooling is an unsung hero using AM techniques. Any aerospace company that is not paying attention to AM tooling opportunities is missing a tremendous advantage. While cost is a driving imperative, many applications see cost savings achieved not just from reduction in recurring production but also in advantages achieved in functionality that serves longer term ROI. Yes, there are challenges facing the introduction to AM. Industry standards, materials characteristics, quality, consistency, process monitoring, surface finish, and software tools are some of the more challenging areas to be overcome. Advances in size and capability are increasing pace due to interests driven by the customer community. Many organizations are jumping into the arena that further accentuates research and application opportunities. Ultimately, AM has a firm foothold in aerospace with an almost exponential growth opportunity. Aerospace is now leading the demand for production grade AM machines [1].

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BIOGRAPHY

Greg Schiller *received a B.S. and M.S. in Astronautical Engineering from the US Air Force Academy in 1985 and AF Institute of Technology in 1992 respectively. He also achieved a MBA from Webster University in 2014. He retired from the Air Force in 2005 in the rank of Lt Colonel. His military career included assignments predominantly in the space career field starting with Space Operations at Shriever AFB and ending with positions at Los Angeles AFB in Space superiority, EELV, and as the Delta II Program Manager. He transitioned to ULA in June 2007 and currently supports ULA's Strategic Planning and Business Development team where he manages ULA's portfolio of Independent Research and Development projects with particular attention on orchestrating the investment strategy for use of Additive Manufacturing.*

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